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Zener Diode Compact Model Parameter Extraction Using Xyce-Dakota Optimization

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Xyce-Dakota Optimization Applied To A Zener Diode Model Parameter Extraction

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Abstract

This report presents a detailed process for compact model parameter extraction for DC circuit Zener diodes. Following the traditional approach of Zener diode parameter extraction, circuit model representation is defined and then used to capture the different operational regions of a real diode's electrical behavior. The circuit model contains 9 parameters represented by resistors and characteristic diodes as circuit model elements. The process of initial parameter extraction, the identification of parameter values for the circuit model elements, is presented in a way that isolates the dependencies between certain electrical parameters and highlights both the empirical nature of the extraction and portions of the real diode physical behavior which of the parameters are intended to represent. Optimization of the parameters, a necessary part of a robust parameter extraction process, is demonstrated using a 'Xyce-Dakota' workflow, discussed in more detail in the report. Among other realizations during this systematic approach of electrical model parameter extraction, non-physical solutions are possible and can be difficult to avoid because of the interdependencies between the different parameters. The process steps described are fairly general and can be leveraged for other types of semiconductor device model extractions. Also included in the report are recommendations for experiment setups for generating optimum dataset for model extraction and the Parameter Identification and Ranking Table (PIRT) for Zener diodes.

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1. INTRODUCTION

The purpose of this study was to pursue a parameter extraction scheme of a Zener Diode adaptable to a semi-automated approach for identifying and optimizing electrical parameters in a standard diode circuit model. A typical electrical device parameter extraction scheme includes an initial extraction by fitting measured behavior of a real diode to elements of a circuit model designed to capture the real diode behavior. Once initial parameter extraction is completed, optimization is invoked to improve the electrical model fit to the measured data, addressing the interconnected response of the individual parameters. This investigation explores the optimization step through a workflow developed with Sandia tools; Xyce and Dakota.[1,2] The methodology of semi-automated initial parameter extraction followed by Xyce-Dakota workflow for final optimization is the proposed approach of *Compact Model Development and Optimization Environment* (CoMoDOE), an improved device parameter extraction and calibration environment for electrical circuit models currently under development at Sandia. The example dataset in this study is that obtained from a standard Zener diode, MMSZ5221BT1 [3] measured under normal environment conditions. This measurement was selected from a larger dataset, which has been collected on as-received, conditioned and aged Zener, Schottky and high voltage diodes with the intent of correlating changes in electrical behavior with physical changes in the devices or as a function of aging time and temperature.

Typical *real* Zener Diode electrical behavior is shown in figure 1-1. For electrical circuit applications, this somewhat complex behavior is categorized into three regions, forward, reverse leakage and reverse breakdown, each indicated in the figure. Within each region, the electrical behavior can be separated into exponential and linear components with respect to the input voltage and is captured in an electrical circuit model consisting of characteristic diodes (for exponential behavior) and resistors (for linear behavior). A difficulty in accurately fitting the electrical response is that the current response to an applied voltage in the reverse leakage region is on the order of 10^{-10} whereas the current response in the reverse breakdown and forward regions is on the order of 10^{-2} . Accurately fitting the measured response across several orders of magnitude as well as transitioning across the respective regions turns out to be a significant challenge in electrical parameter extraction of real diode behavior.

To accomplish the goal of parameterizing the diode circuit model, the general flow followed for this test case is shown in figure 1-2. It is similar to a typical approach used to parameterize any diode circuit model and captures the initialization followed by optimization methodology. Each of the three dashed gray boxes represents parameter sets extracted from the three identified regions in figure 1-1. Within the gray boxes, the methodology is broken into the individual electrical parameters to be extracted from the circuit model, which is described in detail in section 2. The arrows in the figure illustrate the flow from extracted initial parameters to final optimization. Through exercising this methodology, results in this report indicate that blind optimization may achieve an acceptable fit to the measured data, but will not define a unique and physical set of parameters for the circuit model. A careful parameter selection process can lead to a uniquely defined set of parameters to fit a model but how parameters are selected comes with choices guided by two criteria: i) which part of the measured electrical behavior is most important to accurately capture and ii) what underlying measured behavior does a specific electrical parameter represent.

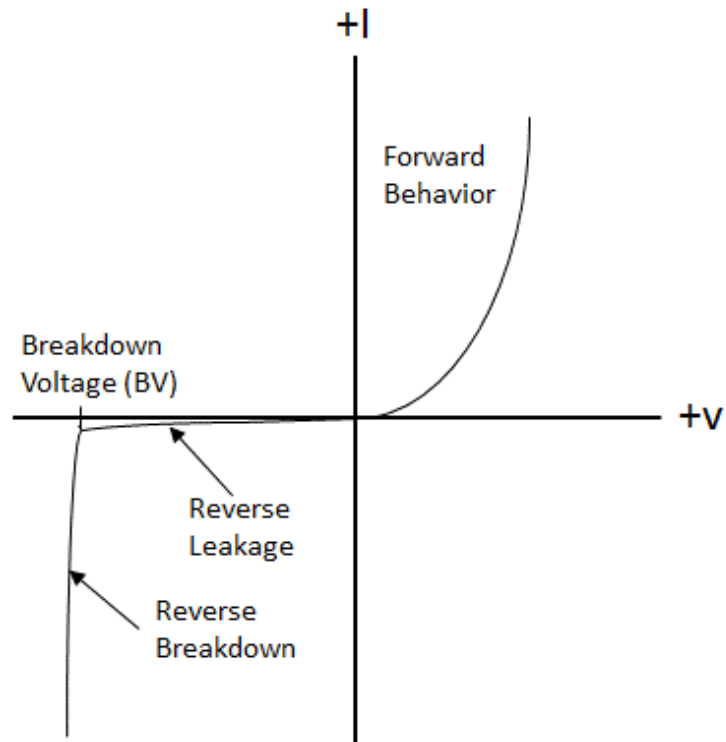


Figure 1-1: Typical Zener Diode electrical behavior.

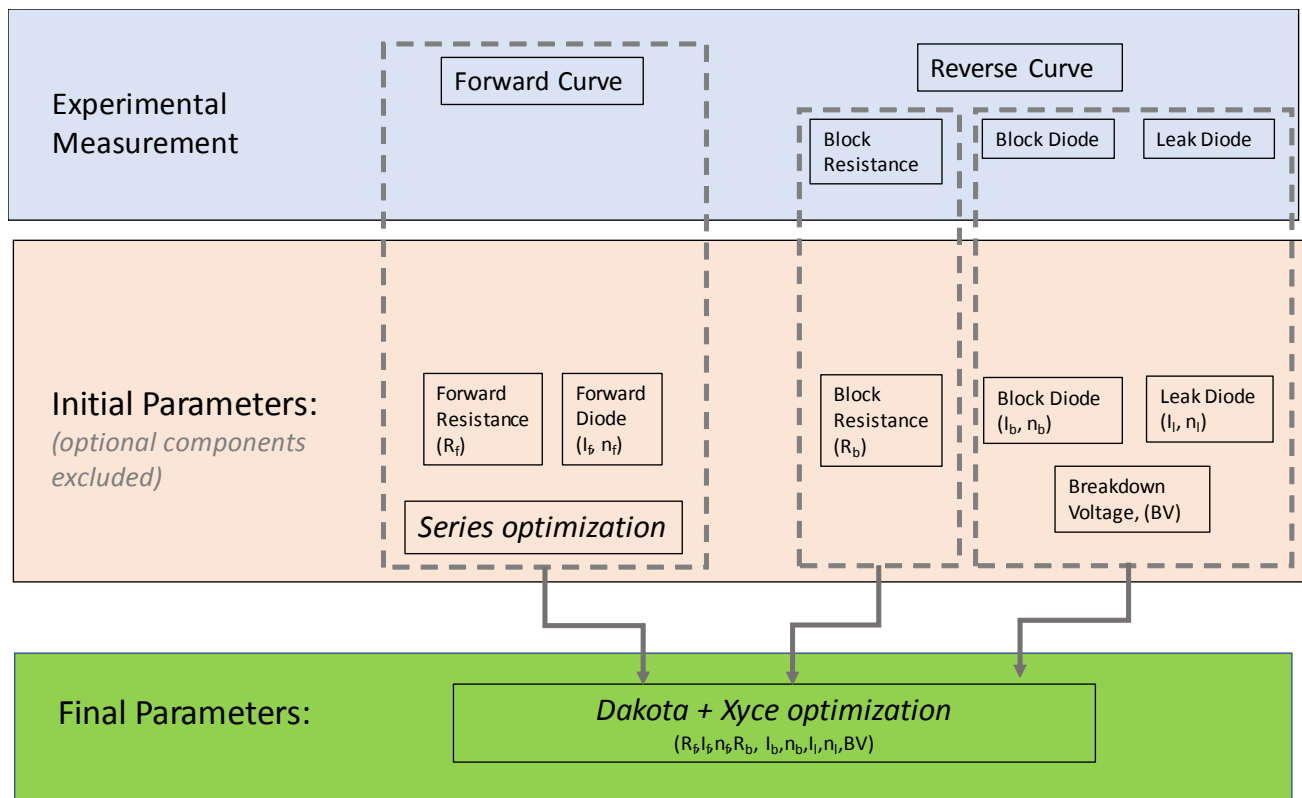


Figure 1-2: Process work flow for parameterizing a Zener Diode using the circuit mode shown in figure 2-1.

2. DIODE MODEL CIRCUIT

Accurate representation of the DC electrical behavior of a real Zener Diode within a macromodel framework has drawn from a family of relatively straightforward circuit models, e.g. [4-6]. The models are similar in that they use multiple well placed circuit elements: characteristic diodes, resistors and an ideal current or voltage source, to capture the measured I-V response of a real diode. The specific circuit model used for this analysis is schematically shown in figure 2-1. Three distinct branches are identified: forward, reverse breakdown (block) and reverse leakage, each of which corresponds to a region of the measured I-V behavior of a real diode identified in figure 1-1 and mentioned in the previous section. The flow for identifying the specific parameters associated with each circuit branch is given in figure 1-2. Although the model is somewhat empirical in nature, the circuit model elements are characteristic electrical components and therefore the parameters they represent reflect more fundamental, physically-based behavior .

Circuit element parameter extraction leads to a circuit model fit to the measured I-V behavior of a real Zener diode and, as already mentioned, is accomplished in two main steps; initial parameter extraction and optimization. During initial parameter extraction, each branch in the model circuit, forward, reverse block and reverse leakage, is fit to a portion of the measured I-V curve it is intended to model. The model circuit, and the position of the characteristic diodes within it, significantly restrict but does not completely eliminate current flow in the inactive branches. That is, when the forward branch is active, capturing behavior in the forward portion of the I-V curve, the reverse block and reverse leakage branches are nearly inactive. Similarly for the reverse block and reverse leakage branches, when either one of these two branches are active, the other two are nearly inactive. Even with the extremely small current flows that exists in the inactive branches of the model circuit, a limited, but important to characterize, dependence exists between the all of the parameters in the circuit model. This dependence can be addressed through optimization. However, parameter optimization without properly extracted initial values, with several parameters available to fit a series of loosely coupled equations leads to an infinite number of possible solutions. Nearly all of these solutions introduce electrical behaviors on circuit branches that were not intended, thus they have unreasonable, non-physical values. Model solutions not corresponding to any physical behavior could have unintended, difficult to discern consequences on larger electrical circuit models which rely on accurately parameterized device models. Therefore, physically meaningful initial parameter extraction is as important as understanding and controlling the role of optimization for

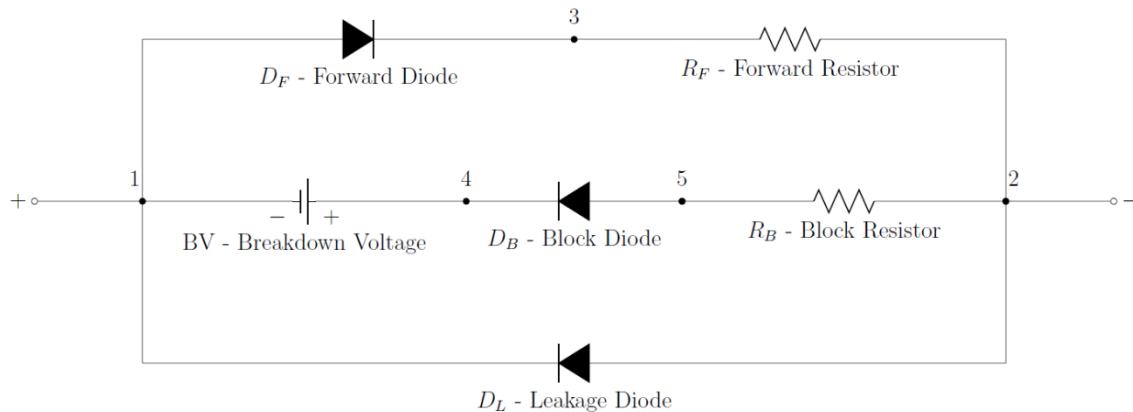


Figure 2-1: Electrical Circuit model used to capture the measured response of a typical Zener Diode.

ensuring that a set of extracted parameters are representative of the circuit elements defined in the model.

The model parameters, defined by the circuit model used for the real Zener diode shown in figure 2-1 and the electrical elements within it, are listed in Table I. Section 3 provides an experimental measurement on a Zener diode tested in a normal environment operating condition and subsequent sections, 4 and 5, discusses initial parameter extraction and optimizing the parameters from a that measured I-V curve. Optimization is performed using a Xyce circuit model – Dakota optimization tool workflow. The workflow was originally developed and employed to optimize the forward diode parameters for a separate research program. [7] This report documents an extended workflow that included all of the Zener parameters and represents the most extensive documentation of this workflow described to date.

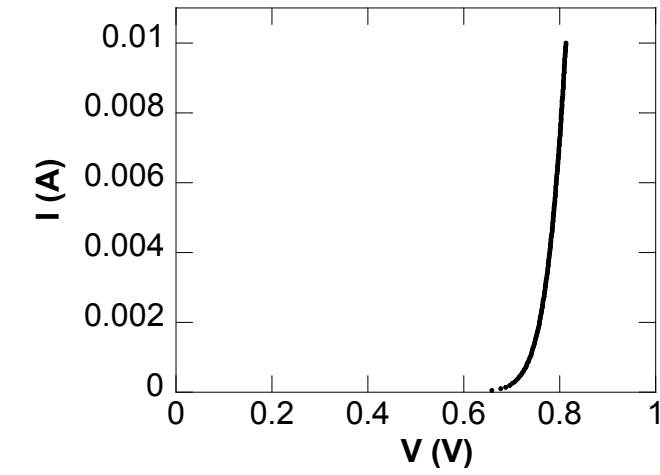
Table I- Zener Diode Circuit Model Electrical Parameters

Parameter	Circuit Branch	Electrical element
I_{sf}	Foward	D_f - Forward Diode
n_f	Foward	D_f - Forward Diode
R_f	Foward	R_f - Forward Resistor
I_{sb}	Reverse Breakdown	D_b - Block Diode
n_b	Reverse Breakdown	D_b - Block Diode
BV	Reverse Breakdown	BV- Breakdown Voltage
R_b	Reverse Breakdown	R_b - Block Resistor
I_{sl}	Reverse Leakage	D_l - Leakage Diode
n_l	Reverse Leakage	D_l - Leakage Diode

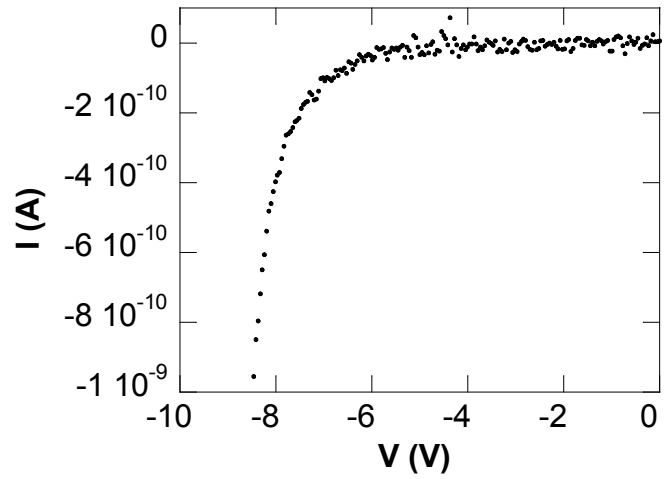
3. EXPERIMENTAL SETUP AND DATA ACQUISITION

In the case of Zener Diode measurements, and more generally the case when parameterizing a circuit model, relevant current vs. voltage (I-V) data spans several orders of magnitude. Therefore, individual measurement sweeps on sections of the I-V response generated by a real diode are taken, each sweep tailored to capture specific portions of the electrical behavior. The portion of the electrical behavior to be captured dictates the increment between individual data points and whether voltage or current is swept. If voltage is swept and current is measured, then in this section, the curve is defined as a voltage-current (V-I) curve. If current is swept and voltage measured, then the curve is defined as an I-V curve. Irrespective of whether voltage or current is the independent parameter for a measurement sweep, the data is still plotted as current vs. voltage and more colloquially expressed as an I-V curve in later sections of this report. During parameter extraction, described in the next section, all data is treated as if current is the dependent variable.

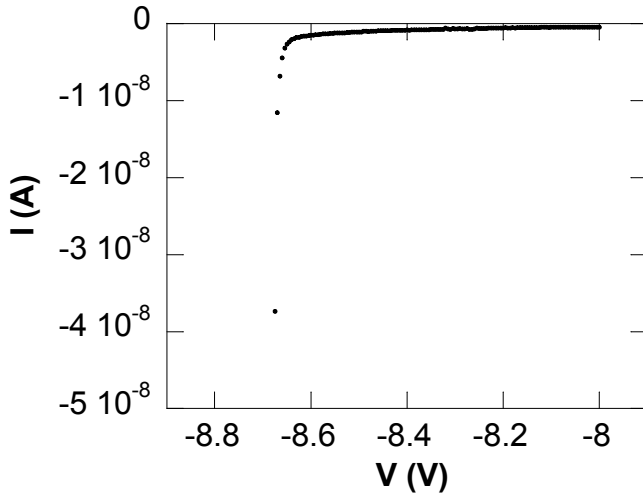
Measured data was collected using the Keysight B1505A Power Device Analyzer/ Curve Tracer equipped with a High Power Source Measurement Unit (HPSMU) and a N1259A test fixture. The HPSMU in this test configuration has a quoted measurement resolution of $2\ \mu\text{V}$, $10\ \text{fA}$ ($1 \times 10^{-14}\ \text{A}$). [8] All measurements were performed using this configuration for all three regions of diode operation (forward behavior, reverse leakage and reverse breakdown as originally defined in figure 1-1). The measurement sweeps were carried out on a MMSZ5221BT1 Zener Diode. [3] Each measurement sweep is shown individually in figure 3-1. For an overview of the electrical behavior of the measured diode, the sweeps are assembled together in composite I-V plots in figure 3-2. Each sweep is meant to focus on generating measurement data for specific parameters and generally relates to a specific branch in the circuit model discussed in the previous section and shown in figure 2-1. Figure 3-1(a) shows the *forward* sweep, meant to generate the data for extracting the forward circuit parameters, those associated with the forward diode (D_f) and the forward resistance (R_f). Figure 3-1(b) shows the *reverse 'Leak'* sweep, meant to generate data for extracting parameters for the leakage diode (D_l). Figure 3-1(c) shows the *reverse 'Block'* sweep, meant to generate data for extracting the block diode (D_b) parameters. Figure 3-1(d) shows the *reverse 'Zener V'* sweep, meant to generate data for extracting the block resistance (R_b). Extraction of the breakdown voltage parameter (BV) can be performed a few different ways, using a combination of the reverse voltage sweeps. The value of plotting data on a semilog y scale, i.e. $\text{Ln}(I)$ vs. V , (Ln denotes the natural logarithm), as shown in figure 3-2(b) emphasizes the low current measurement regions and is an extremely useful construct for extracting parameters by linearizing the exponential behaviors from the measured data, as will be shown in the next section.



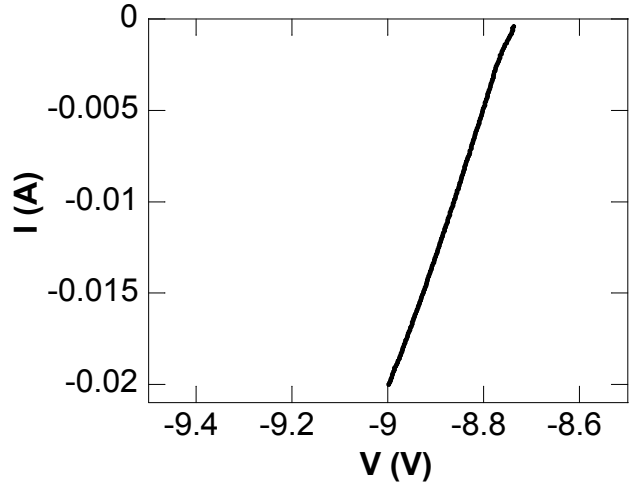
(a) Forward I-V sweep, current step = 5×10^{-5} , range 0-0.01 A.



(b) Reverse 'Leak' V-I sweep, voltage step = 0.05, range 0-9V.



(c) Reverse 'Block' V-I sweep, voltage step = -0.005, range -8 to -9V.



(d) Reverse 'Zener V' I-V sweep, current step = -1×10^{-4} , range 0 to -0.02 A.

Figure 3-1: Measurement of a MMSZ5221BT1 Zener Diode. Swept ranges shown in (a-d) focus on capturing data for specific model parameters.

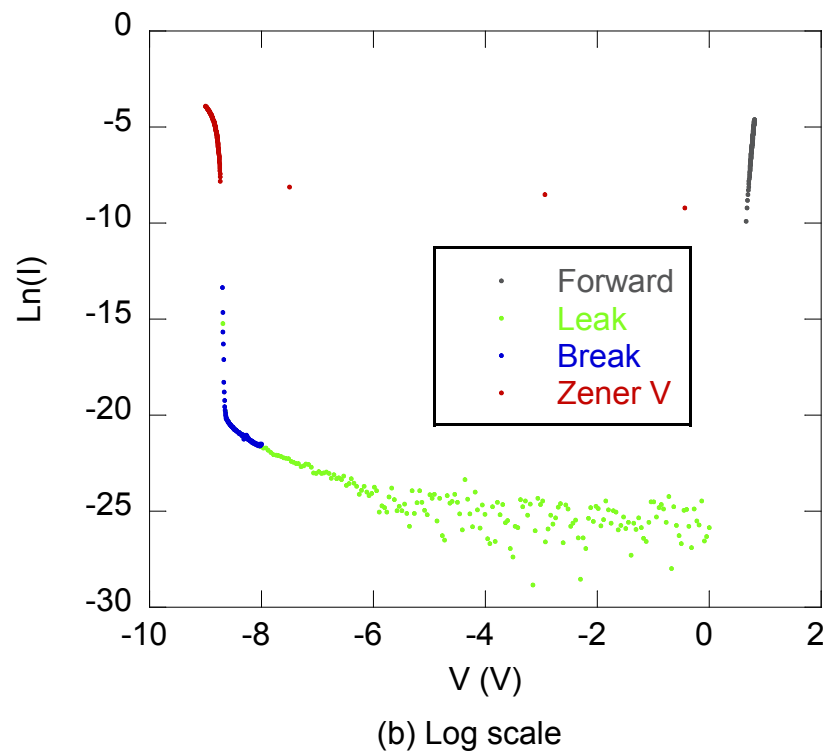
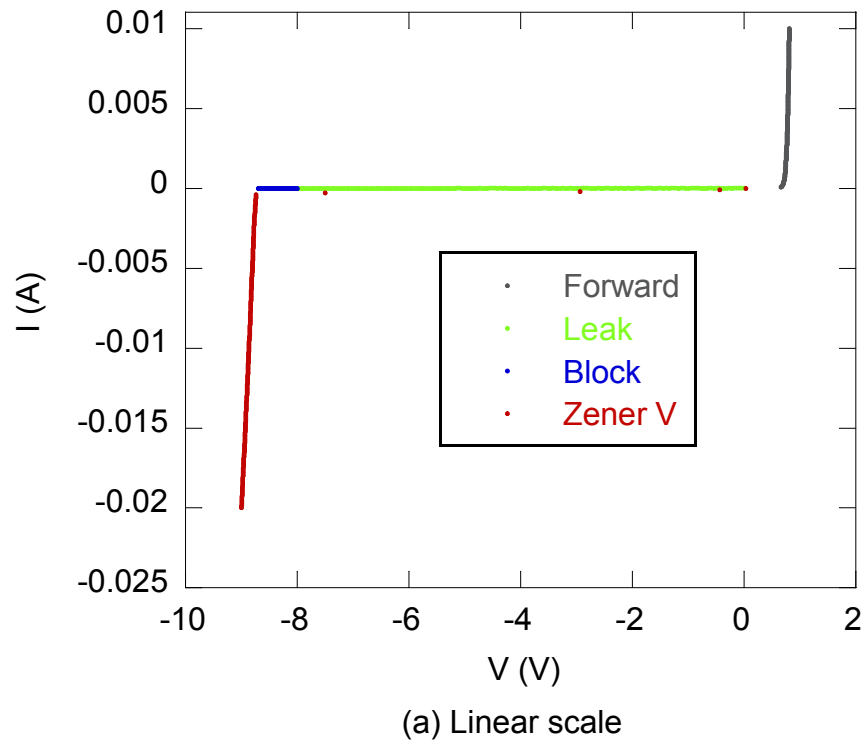


Figure 3.2: All experimental measurements plotted together for the representative measured Zener Diode.

4. INITIAL PARAMETER EXTRACTION

Initial parameter extraction for the circuit elements individually shown in the real Zener diode circuit model in figure 2-1 follow a common approach. All circuit element diodes, in place to capture exponential electrical behavior, are modeled as characteristic diodes using the well-known Ebers-Moll equation [9]:

$$I_D = I_S(e^{V_D/nV_t} - 1) \quad (1)$$

In Eq. (1), I_D and V_D are the respective current passing through and voltage drop across the diode. $V_t = kT/q$, where q , k and T represent electronic charge, boltzmann's constant and temperature in degrees Kelvin; it is a single normalizing term representing a straightforward convolution of these fundamental physical and thermal quantities, and is often referred to as the thermal voltage. I_S and n are the saturation current and emissivity coefficients, they serve as fitting parameters for each of the diodes in a circuit model. A linearized version of Eq. (1) for a characteristic diode is given by Eq. (2):

$$\text{Ln}\left(\frac{I_D}{I_S} + 1\right) = \left(\frac{1}{nV_t}\right)V_D \quad (2)$$

Parameters I_S and n are initialized from this linear form using equations 3 and 4:

$$n = \frac{1}{mV_t} \quad (3)$$

$$I_S = e^b \quad (4)$$

where m and b represent the slope and y axis of a plotted curve resulting from applying Eq. (2) to the appropriate portion of measured data converted to V vs. $\text{Ln}(I)$ form, e.g. figure 3-2(b). The '+ 1' term, which is negligibly small in at forward bias condition except at very low biases, is neglected in Eq. (2) to extract initial diode parameters.

Resistance parameters, R_f and R_b , are parameterized by capturing some aspect of ohm's law *i.e.*, the effect of resistive loss, from the appropriate portion of the measured data. The most obvious approach is to extract the slope V/I from the appropriate section of measured data, initial resistance parameters are extracted using some variation or extension of that approach. Xyce and other typical SPICE [6] circuit models include a parasitic resistance parameter in their diode device model implementations, which may be used to implicitly capture these resistance parameters.

4.1 Forward Parameters

This section reviews the parameterization of the forward behavior of a Zener diode using the measured forward sweep shown in figure 3-1(b) and defined by circuit elements D_f and R_f of the forward branch of the Zener diode circuit shown in figure 2-1. D_f is a characteristic diode whose behavior is defined by Eq. (1), the parameters to be extracted from the measured data are I_{Sf} and n_f , as listed in Table I. Following the approach outlined at the beginning of this section for extracting characteristic diode parameters, figure 4.1-1 shows the forward sweep measured data plotted on $\ln(I)$ vs. V axes. The portion of the data which defines the D_f behavior is at low current, where electrical behavior defined by forward resistance, R_f , is vanishingly small. Figure 4.1-1 reveals that the lower voltage region of the forward curve in $\ln(I)$ vs. V space is linear, as expected for the exponential form of characteristic diode behavior. In this case, the first six measurement points in the curve (those with the six lowest voltages) were fit to a line, also shown in the figure. The fitted line yielded a slope and intercept value with the $\ln(I)$ axis from which respective I_{Sf} and n_f values of 5.62×10^{-16} and 1.011.

The deviation from linearity in the plot shown in figure 4.1-1 is the deviation from characteristic diode behavior captured by the series resistor shown in the forward branch of the model circuit (figure 2-1) or the R_f parameter. The high current region, where the forward resistance drives the deviation from linearity on this plot, is used to initialize the R_f parameter. In linear space, the slope of the I - V curve in figure 4.1-1 will begin to trend toward a linear slope that generated by the forward resistance parameter as the current increases. To accurately parameterize this value, plotting the slope of the measured curve ($\Delta V / \Delta I$) vs. $1/I$ provides a result which can be linearly extrapolated to a zero $1/I$ value, interpreted as infinite current, to provide an accurate R_f extraction, as shown in figure 4.1-2. The extracted value for R_f is 1.414Ω using this approach.

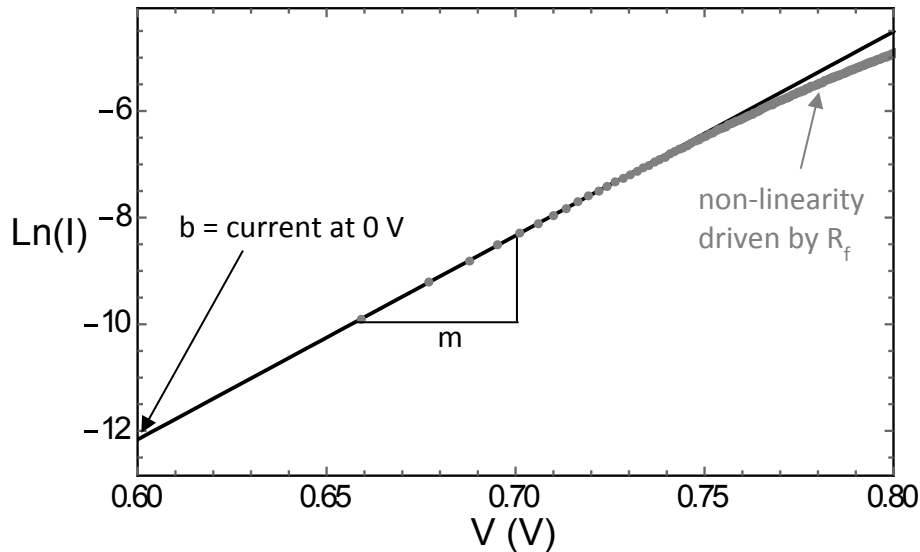


Figure 4.1-1: Forward sweep data plotted on $\ln(I)$ vs. V axes. Linear fit to the low voltage data in this space allows for parameter extraction defined by the characteristic diode D_f .

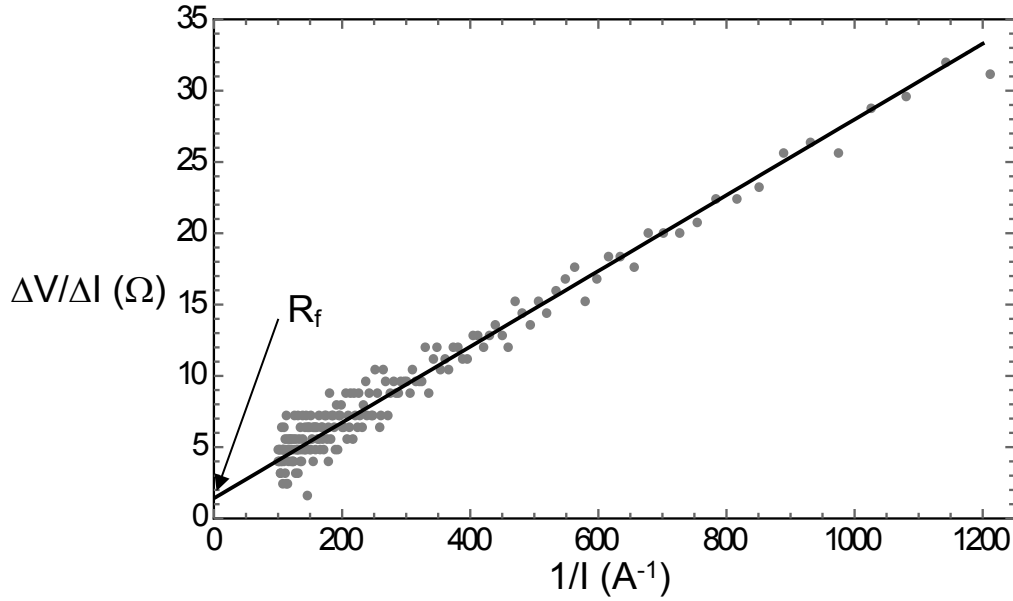


Figure 4.1-2: Forward sweep data plotted as $(\Delta V/\Delta I)$ vs. $1/I$ revealing extraction of R_f .

Eq. (5) listed below, expresses the I-V relationship of the forward circuit branch in the Diode model as a single equation. Performing a non-linear fit to eq. (5) using the initial parameters as a starting point to allows for additional refinement of the forward parameters.

$$V = nV_t \ln \left(\frac{I}{I_{sf}} + 1 \right) + IR_f \quad (5)$$

Figure 4.1-3(a) compares the model behavior using Eq. (5) and the initial parameters with the measured forward data. A nonlinear regression fit to eq. (5) using the standard statistical fitting function **NonLinearFit[]** in Mathematica® [10] was performed using the initial parameters as starting values, yielding the result listed in the third column of Table II and the comparison plot shown in figure 4.1-3(b). Excerising a non-linear curve fit to the initial parameters provided a small correction to the initial parameters leading to an further improvement of the model fit to the measured data. A Xyce-Dakota workflow can also lead to a fit equivalent to that shown in figure 4-3(b) to the forward measured data, as will be shown in section 5.

Table II – Forward Parameters		
Parameter	Initialized	After Non-Linear Curve Fit
I_{sf}	5.620×10^{-16}	4.422×10^{-16}
n_f	1.011	1.002
R_f	1.414	1.683

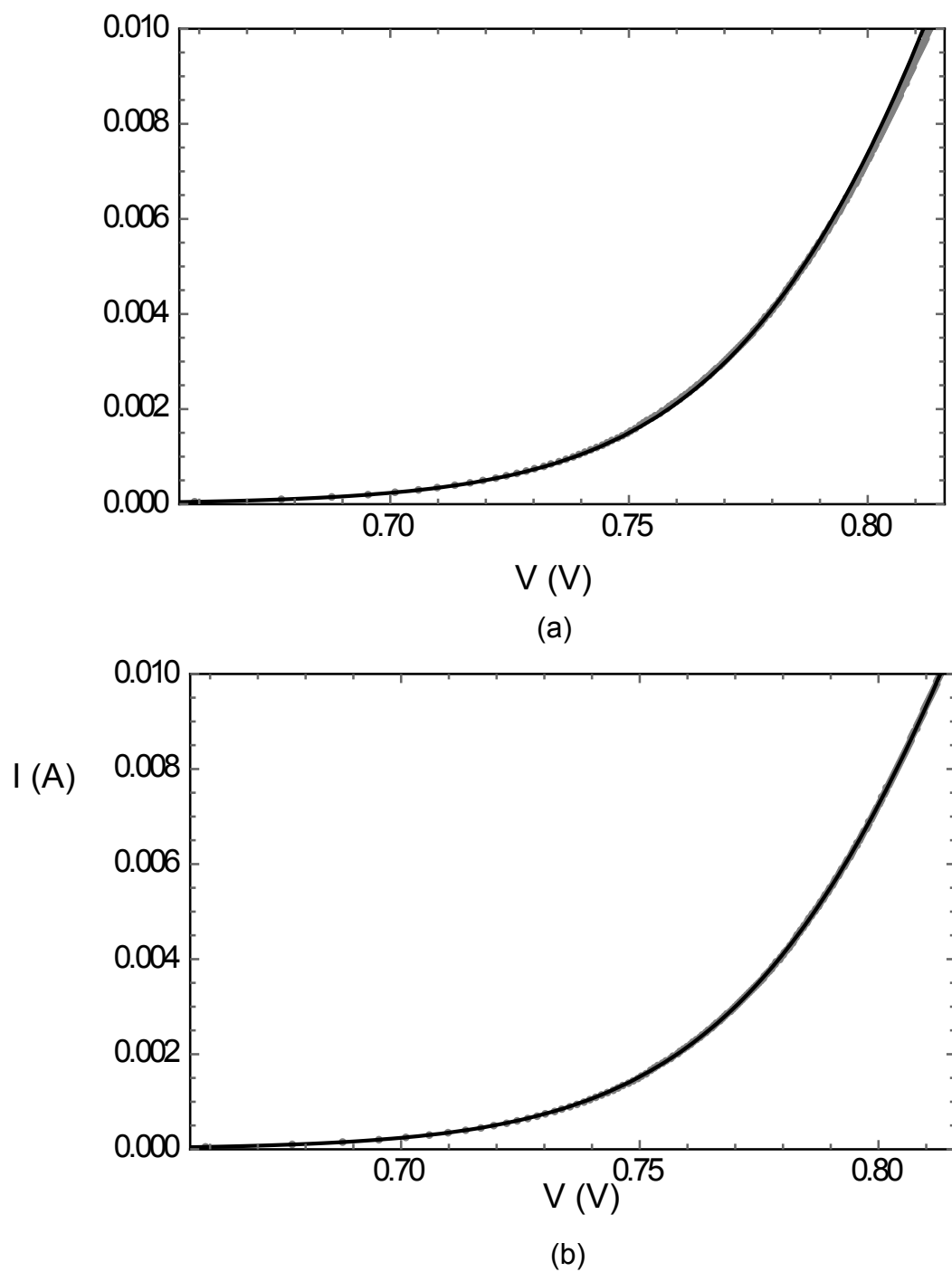


Figure 4.1-3 – Fit to forward data (a) using initial parameters and (b) after non-linear fit to equation (5).

4.2 Reverse Parameters

Ideally, data from each segment of the experimental measurements is used to initialize parameters for each model circuit component for the corresponding branch. In the case of the reverse parameter extraction, the ‘reverse leak’ measurement is meant to be used for the reverse leakage diode parameter extraction. The ‘reverse block’ measurement is meant to be used for the block diode parameter extraction. The ‘post breakdown’ measurement is meant to be used to extract the post breakdown block resistance. To help discern low current leakage behavior, figure 4.2-1 shows low current measurement data in the reverse direction on an expanded current scale. Most of the data shown on the plot is captured during the leak sweep measurement which are shown as gray data points. The figure suggests a reasonable assumption is to set resolution limit on the measurement data to 5×10^{-11} A. By screening out all data with a current measurement equal to or less than this value the portion of the data that can be utilized to extract parameters for the leak diode, D_1 in figure 2-1 becomes evident.

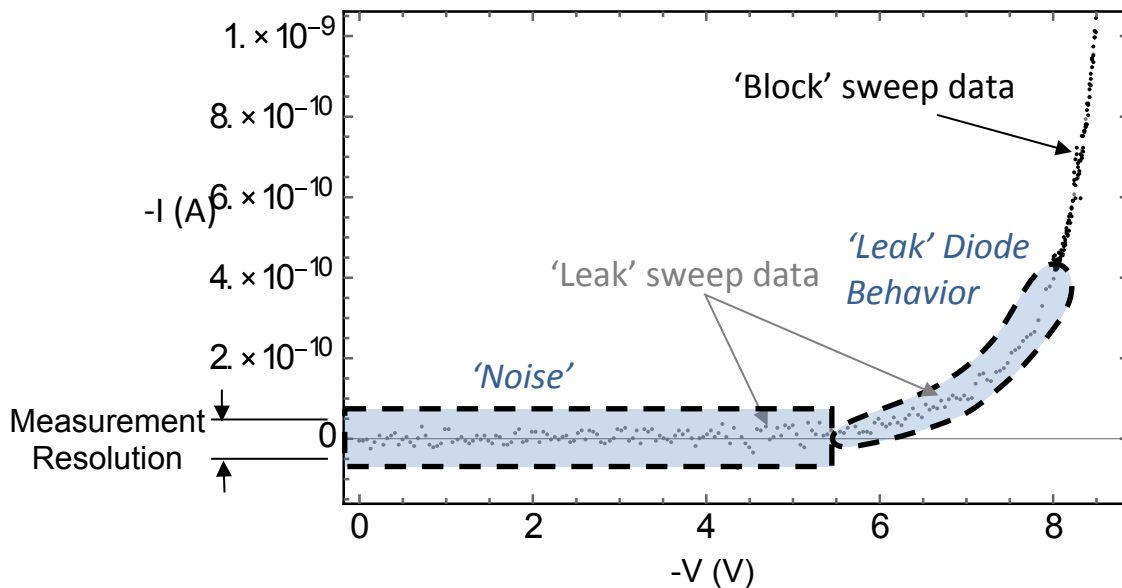


Figure 4.2-1 – The reverse leakage measurement data and a portion of the block measurement data plotted on an expanded current scale. Regions delineated as ‘noise’ and ‘leak diode behavior’ are indicated.

Excluding the measurements with current values less than $\pm 5 \times 10^{-11}$ A in magnitude and plotting the reverse leakage and reverse block measurement data in $\ln(I)$ vs. V space, as shown in figure 4.2-2, reveals linear portions of the data in this space from which initial reverse leakage diode parameters, I_{sl} and n_l and reverse block diode parameter n_b can be extracted. The fits used to extract these parameters are shown by the blue lines. The intersection of these lines provides an initial value of the breakdown voltage (BV) parameter. A portion of the block diode data, shown as black points in figure, reveals a portion of the data not captured by either the Leak Diode fit or the Block diode fit. The expectation is that resultant parameterized model prior to optimization will not accurately fit measured data, or real diode behavior, in the small region between 8.1 and 8.5 V. The three parameters extracted from the slope and intercept values of the leak diode fit and the slope of the block diode fit were found by exercising equations (3) and (4). They are listed in Table III. Note that a reasonable initial value for the I_{sb} parameter, the leakage of the characteristic block diode

cannot be extracted from the block diode fit shown in figure 4.2-2. This is because the element representing the breakdown voltage lies in the same branch as the block diode element confounding that parameter extraction.

A linear fit, shown in figure 4.2-3, to the post breakdown data was performed to extract R_b , the diode resistance after reverse breakdown. Extrapolating the linear fit to zero current gives a result of about 8.74 V, which provides a poor estimation of the BV parameter to be used in the circuit model defined in figure 2-1.

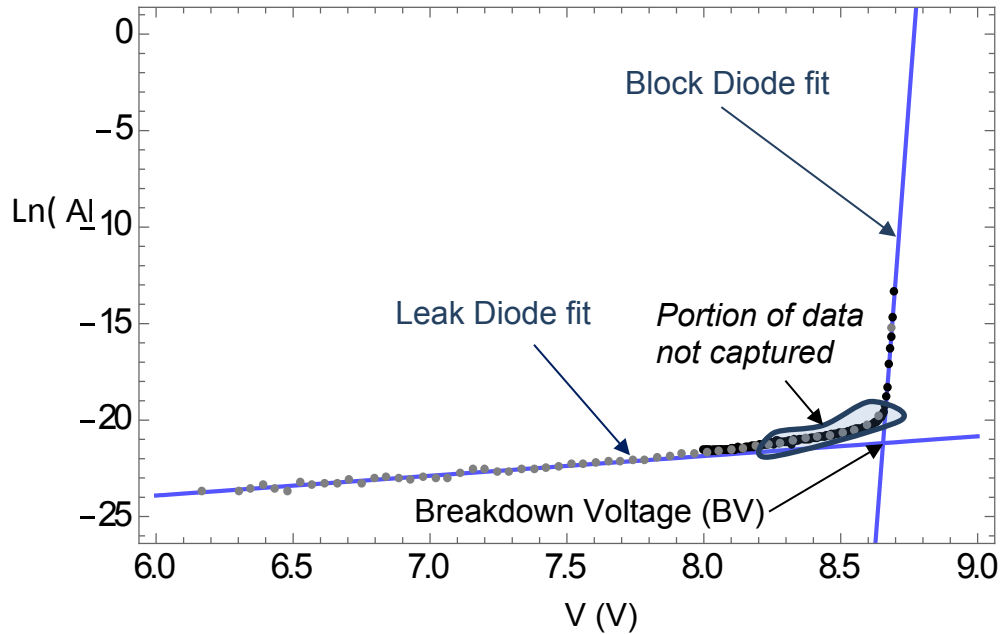


Figure 4.2-2: The reverse leakage and block measurement data plotted on a $\ln(I)$ vs. V scale. Portions of data used to extract initial Leak Diode (I_{sl} and n_l) and Block Diode (n_b) parameters indicated. Location of extracted initial BV parameter also indicated.

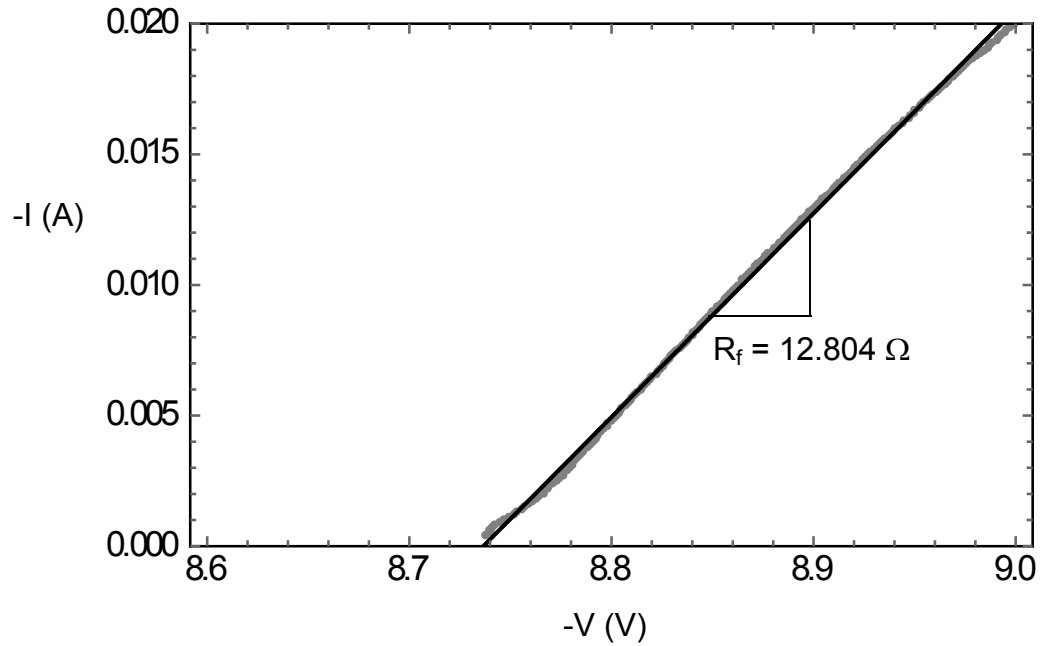


Figure 4.2-3 – Linear fit to ‘Zener-V’ post breakdown measurement to extract R_b .

Table III – Initial Reverse Parameters		
	Initial Value	Comment
I_{sl}	8.881×10^{-14}	From fit to data between 6 and 7.5 V
n_l	37.81	From fit to data between 6 and 7.5 V
I_{sb}	$\leq 1 \times 10^{-14}$	Begins to influence reverse leakage at values larger than 1×10^{-14} (see section 5)
n_b	0.2081	From fit to block data, last six points
BV	8.654 V	Intercept defined by block and leak fits
R_f	12.804 Ω	Linear fit to post breakdown data

4.3 Circuit Simulation-Measurement Comparison with Initial Parameters

With the set of extracted initial parameters shown in Table II and Table III, a simulation of the real diode I-V behavior using the circuit model shown in figure 2.1 was configured and run using Sandia National Laboratories' Xyce circuit simulation tool and compared with measured data. The Xyce simulation results are shown as a series of comparison plots against the experimental measurement in figure 4.3-1. The plots show a comparison on a linear scale generally fits the measured data well. A more detailed comparison across the reverse breakdown region, shown in figure 4.3-1(b) on a linear scale and 4.3-1(d) on a Ln(I) vs. V scale, show that the only region where the simulation does not accurately capture the measured response is at reverse breakdown.

Understanding why initial parameters provides a poor fit in the reverse breakdown region, but an excellent fit in the reverse leakage and forward regions of the measured behavior provides insight into interparameter dependences and non-uniqueness of the parameterized circuit model used to model the real diode behavior. In turn, this insight leads to strategies for minimizing those

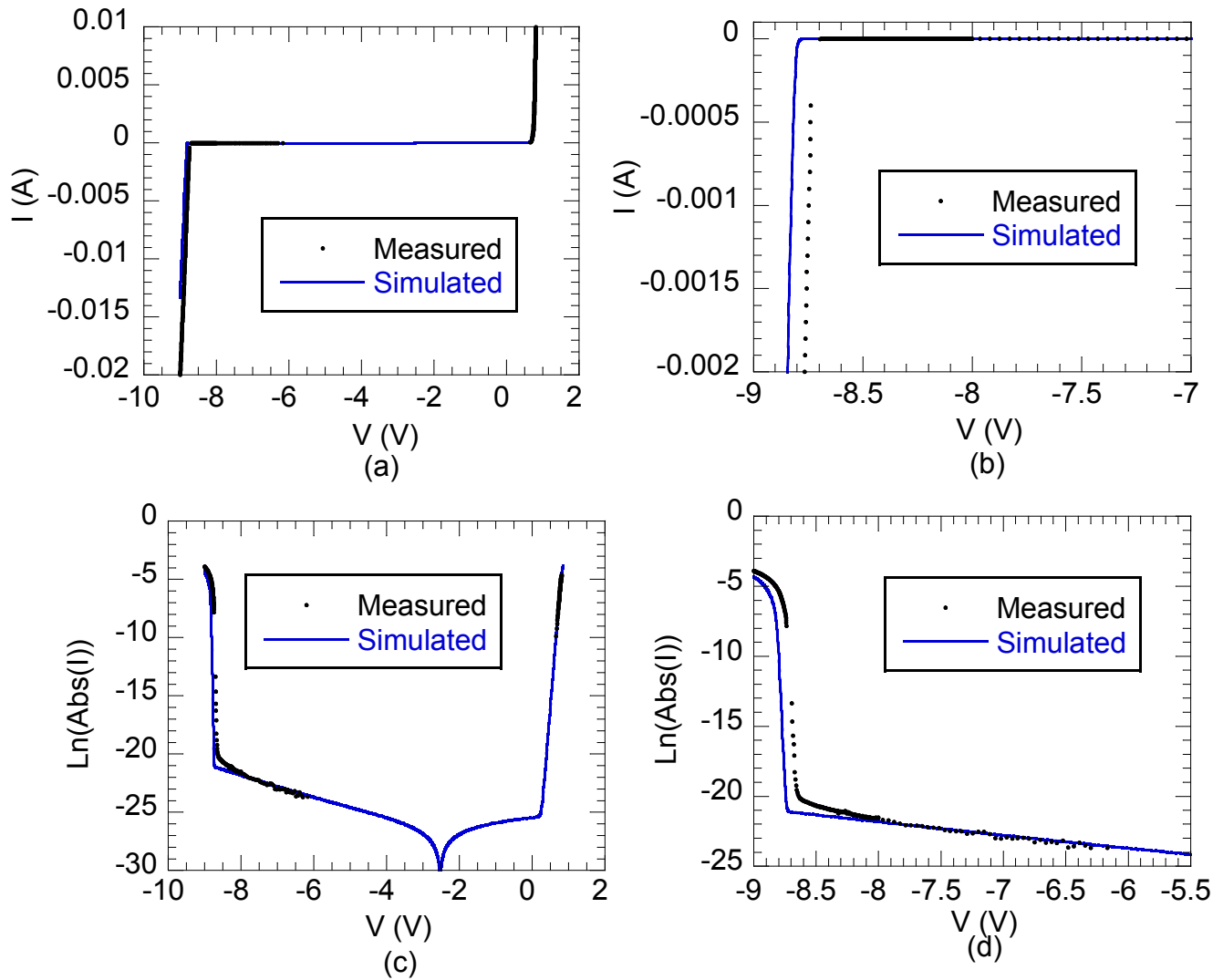


Figure 4.3-1 Xyce simulation compared with measured data using initial parameters. (a) Linear Scale (b) Linear scale in reverse breakdown region. (c) Ln(I) vs. Voltage scale. (d) Ln(I) vs. Voltage in reverse breakdown region.

dependences and improving the final optimization step. A first step to understanding these dependences is shown in figure 4.3-2, results from a simulation that does not include the reverse breakdown branch of the real diode compared with the measured data. Without the reverse breakdown branch, the breakdown circuit elements, D_b , BV , and R_b and their respective parameters, I_{sb} , n_b , BV and R_b are not included in the Xyce circuit simulation. The comparison, presented in both linear and $\ln(I)$ vs. V plots, demonstrates that the simulation still accurately captures the reverse leakage and forward portions of the measured diode electrical response and that within the reverse leakage and forward regions in the real diode I-V response, there is only a shift in the very low current region which no measured data exists. Thus, the defined breakdown circuit element parameters have a negligible impact on the fit to the measured data in the reverse leakage and forward regions. They only govern the fit to the measured data in the reverse breakdown region of the real diode response.

With the understanding that the reverse breakdown parameters do not appreciably impact the model fit to the measured forward and reverse leakage data, adjusting the fit to breakdown behavior can be readily investigated. Amongst the breakdown parameters, R_b controls the linear slope of the simulated response at high measured reverse currents and with the initial value of R_b , extracted via the plot shown in figure 4.2-3, this slope is captured accurately in the simulation, as best shown in figure 4.3-1(a). n_b captures the exponential slope of the measured data just past breakdown, its extraction relies on a limited number of data points from the block diode measurement, shown in figure 4.2-2, and the simulation fits this slope in the measured data in that small region well, as shown in figure 4.3-1(d). Varying this parameter degrades that fit. Therefore, sensitivity of the fit between the simulation and measurement in the breakdown region can be pared down to I_{sb} and BV . Varying I_{sb} and BV while holding all other model parameters fixed to the values listed in Table II and Table III in Xyce circuit simulations and comparing those results to the measured behavior elucidates how these interrelated parameters impact the model fit. To this end, figure 4.3-3 shows how varying I_{sb} impacts the model fit and figure 4.4-4 shows how varying BV impacts the model fit to the measured behavior. Both parameters shift the fit to the post breakdown behavior without

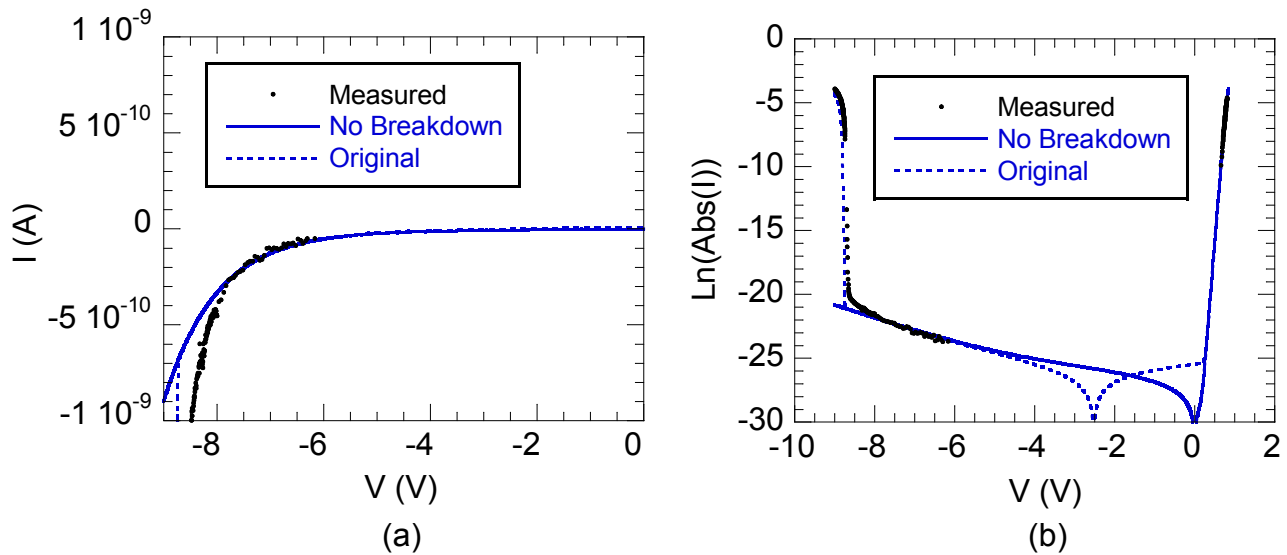


Figure 4.3-2 (a) Comparison of measured data, Xyce simulation with no breakdown parameters and original Xyce simulation shown in figure 4.3-1 with initial parameters in reverse breakdown region. (b) Same comparison on a $\ln(\text{current})$ vs. Voltage plot and across reverse and forward regions.

changing the slope to the post breakdown curve. Figure 4-3-3(b) also shows that high values of I_{sb} , greater than 10^{-12} , begin to impact the fit to the measured reverse leakage behavior. Thus, these results demonstrate that significant redundancy exists between I_{sb} and BV . The only requirement on I_{sb} prior to any additional optimization is that it is held below a value, (at least 10^{-12}) where it does not impact the model fit to the available measured data in the reverse leakage and forward regions. Assuming this value must be large enough that it does not impact the precision capability of the simulation tool, Table III conservatively places it as 1×10^{-14} A.

The cusp that appears on the $\text{Ln}(\text{Abs}(I))$ vs. V plots of the simulated results is an artifact of taking the absolute value of the current before converting to the natural log (Ln) of the current. It indicates where the current crosses zero on the simulated result. This location shifts to zero voltage in the case of the simulation with no breakdown parameters. The location of this crossover point on the voltage axis is driven by the R_b parameter. Within the range of values exercised for the results given in figure 4.3-3 and 4.3-4, BV does not impact this location at all and I_{sb} does only when its value is greater than 10^{-12} . Conjecture based on the analyses that led to the results in this sub-section suggests that finding and fixing optimal BV , R_b and I_{sb} parameters to accurately fit the measured results in the breakdown region then re-optimizing the leakage parameters I_{sl} and I_{sf} is a method to achieve an improved fit in the extremely low current forward and reverse leakage regions of the measured real diode behavior. In the measured data presented here, a dearth of accurate data in this extremely low current region, indicates that re-optimizing I_{sl} and I_{sf} is not will not improve the model fit to the measured data.

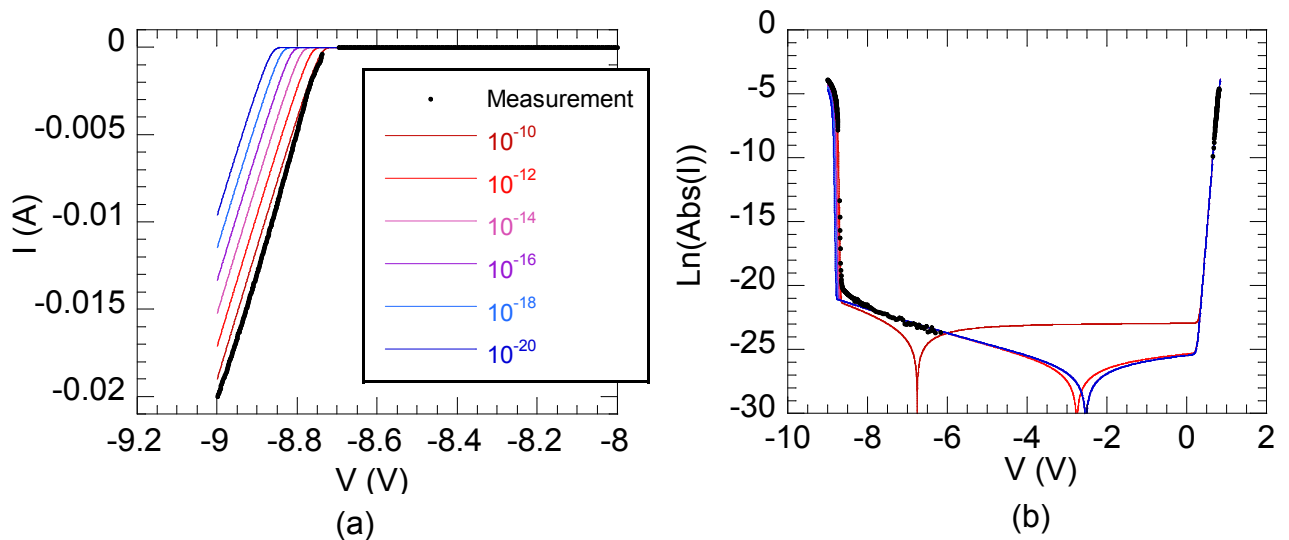
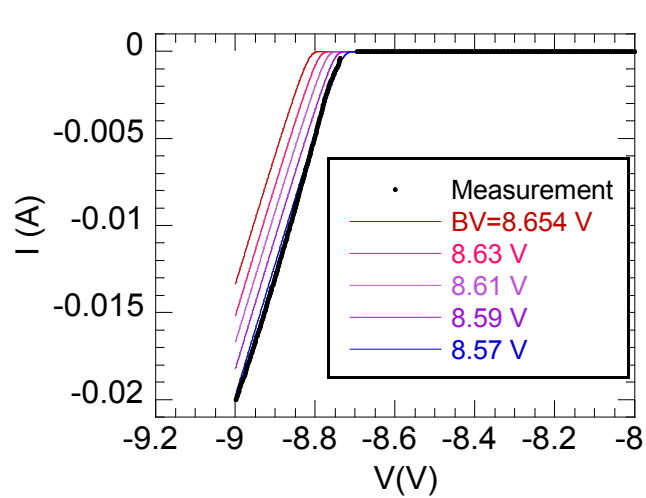
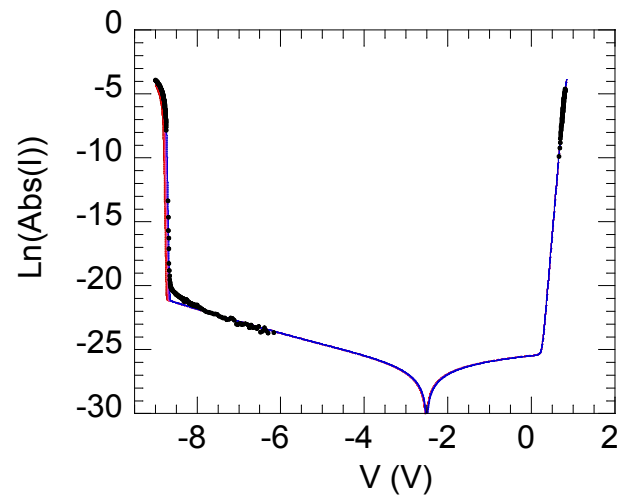


Figure 4.3-3: I_{sb} variation on Current vs. Voltage plots, $BV=8.654$ V. (a) linear I vs. V and (b) $\text{Ln } I$ vs V .



(a)



(b)

Figure 4.3-4 Breakdown Voltage variation on Current vs. Voltage plots, $I_{sb}=10^{-16}$. (a) linear I vs. V and (b) $\ln I$ vs V .

5. OPTIMIZATION WITH XYCE AND DAKOTA

Optimization is performed using a combination of the two Sandia National Laboratories ASC program simulation tools, Xyce and Dakota, [1,2] using script written in the open source programming language platform Python that passes information into and facilitates communication between the two ASC codes. The calibration workflow utilizing Xyce, Dakota, and Python script originated from Keiter *et al.* [7]. While Xyce is the circuit simulator described in the previous section; Dakota contains algorithms for gradient-based optimization methods. For this application, Dakota provides an interface to the nl2sol [2] algorithm to perform a non-linear least squares optimization of the simulation output against the experimental data. The Xyce netlist contains a parameterized version of the device model, as described in the previous section, *and* contains commands to perform a DC sensitivity analysis on each parameter with respect to a user-defined objective function. The resultant analytic sensitivities [1,7] provide gradients to determine the next step in the optimization process. The workflow starts with Dakota utilizing a bash script to execute Xyce using a netlist with the initial set of model parameters, those found in section 4, as the input. Xyce executes the the netlist and generates an output file which includes parameter sensitivities and simulated electrical behavior in a format expected by the nl2sol algorithm. The Dakota nl2sol algorithm updates the parameters which are then processed into an updated Xyce netlist using Python scripts. The updated netlist is again executed in Xyce using the same bash script, closing the loop on the iterative optimization process. Optimization continues until a convergence criterion defined within Dakota is met. The objective function used by Xyce for calculating the parameter sensitivities is:

$$Ln_{10}^{[10]}(abs(I(V_{in}))) \quad (6)$$

where V_{in} is the voltage applied to the Zener Diode and the $abs(\cdot)$ function represents the absolute value function ensuring current values are in the positive domain prior to computing the logarithm. This is essential in producing a good calibration result as it more evenly distributes the weight of the current output which spans several orders of magnitude.

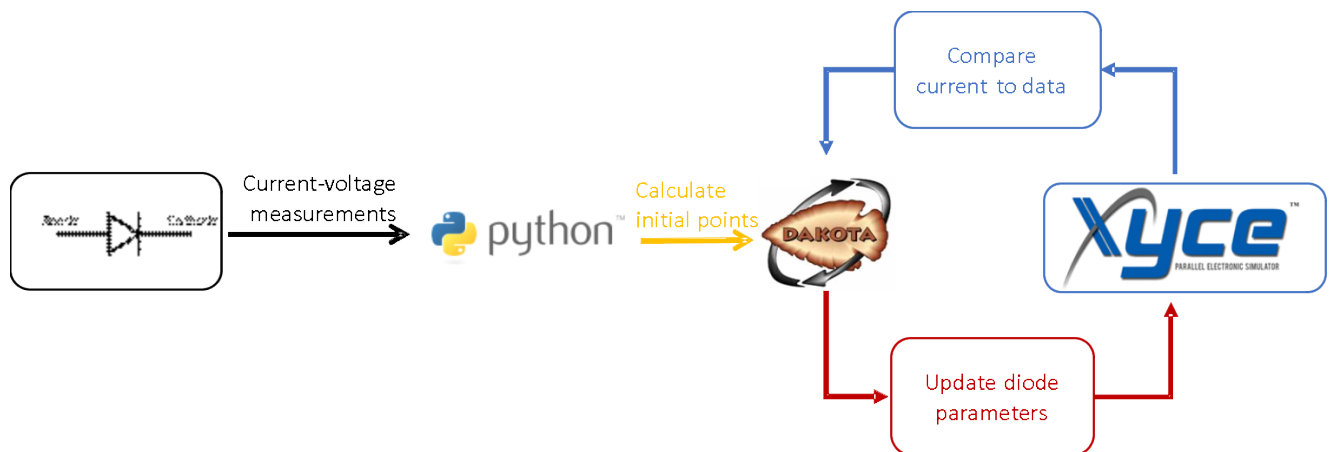


Figure 5-1: a schematic illustrating the process utilizing a Xyce-Dakota framework for parameter optimization.

Multiple Python scripts are used to condition and pass data between Xyce and Dakota. Conceptually, a Python script can also be used to generate initial parameters, as outlined in section 4, and then pass the initial parameters to be used in a Xyce-Dakota optimization run. Considerable communication must be written in Python to execute the Xyce-Dakota link smoothly, including:

- Adjusting the file formatting and conditioning the data between the two tools
- Transformation of the experimental data via the objective function
- Formatting and regridding of the simulated data to match the experimental data

Once the Dakota-Xyce optimization workflow was established and confirmed to be functioning correctly, several cases were executed to determine the effectiveness of the optimization tool in realizing an improved fit to the measured data. Two of those cases are presented here: i) optimize forward fit with forward parameters and ii) fix the forward parameters and two of the reverse parameters (n_b and I_{sl}) then allow the Dakota-Xyce workflow to optimize the remaining parameters.

Case I- Optimize the fit to the forward I-V data

Optimization of the forward circuit branch fit to the measured data was the first test of the Dakota-Xyce optimization workflow. Knowing that optimizing the initial parameters using a standard non-linear curve tool already provided an excellent fit to the measured data, the objective of this exercise was to demonstrate the power of a Dakota-Xyce optimization tool for achieving an equivalent fit without the burden of having to perform an initial parameter extraction. Thus, initial parameters were set to order of magnitude level guesses with generous bounds. Table I lists the initial guesses, optimization was run until a convergence tolerance of 10^{-6} was met resulting in the ‘after optimization’ values also listed in the table. For comparison, the values found with the parameter extraction and non-linear curve fit approach outlined in section 4.1 are also listed. The accuracy of fit achieved by the Dakota-Xyce optimization proved indistinguishable to that found to the prior non-linear curve fit.

The fact that optimized parameters are not identical demonstrates that the three parameter model/solution to the forward data is non-unique and that combination of parameters using the forward circuit model shown in figure 2-1 achieve an equivalent (nearly perfect) fit to the measured

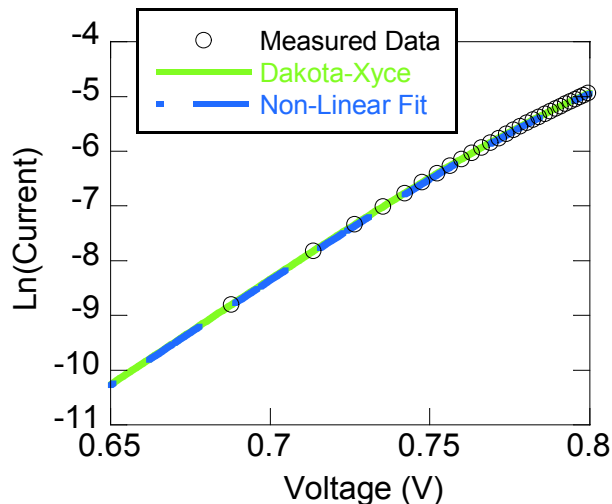


Table IV- Results from optimizing forward parameters			
Parameter	After Non-Linear Curve Fit	Initialized For optimization	After optimization
I_{sf}	4.422×10^{-16}	1×10^{-20}	3.79×10^{-16}
n_f	1.002	1.000	0.9956
R_f	1.683	1.000	1.744

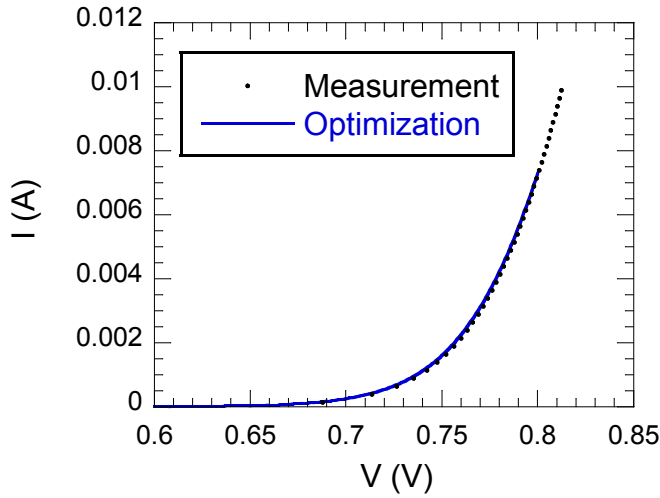
Figure 5-2: Comparison of Dakota-Xyce optimization with the forward measured data and a Non-Linear curve fit. Results demonstrate excellent agreement between model fits and measured data.

data. Although not proven in this test case, this result suggests the choice of final parameters is likely driven by the objective function used in the optimization process and that equivalent acceptable solutions bounded by a narrow range for all three parameters.

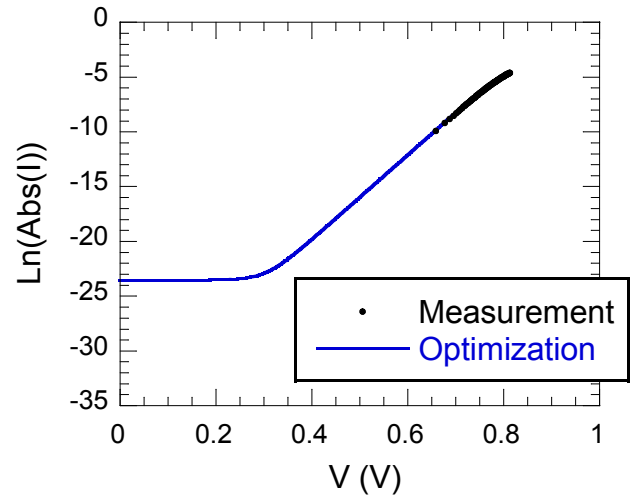
Case II- Fix the forward parameters and two of the reverse parameters (n_b and I_{sl}) then allow Dakota-Xyce to optimize the remaining reverse parameters

The end of section 4.3 suggests that a best approach for improving the model fit beyond that provided by the initial parameter estimations is to optimize the BV parameter while estimating and fixing I_{sb} to a sufficiently low value then holding all other parameters fixed to their initially estimated values. However, optimizing a single parameters is not a sufficient test of a Xyce-Dakota workflow and does not further the path of a Xyce-Dakota optimization framework within Comodoe development. Thus, the Xyce-Dakota workflow was set to optimizing several of the reverse parameters while holding n_b , I_{sl} and the forward parameters fixed. Table 5-2 summarizes the initial values, bounds on those values prescribed in the optimization and the optimized results for all of the parameters in the circuit model. Parameters whose values were held fixed are indicated with a '#' and their values are italicized. The optimized results are also given in the table and shown in figure 5-3. The result demonstrates the interdependence of the I_{sb} and BV parameters. A value of I_{sb} was found that best fit the post breakdown data and provided an improved fit to the available measured data prior to breakdown, approximately the -6V to -8V range. Small adjustments were made to each of the other parameters. The optimized value of I_{sb} is high, impacting the model behavior between -5V to 0.6 V in a manner consistent with the analysis in section 4.3 and the result shown in figure 4.3-3(b). An equivalent fit, without shifting the model behavior between -5V to 0.6 V could have been achieved by weighting the optimization toward shifting the BV parameter, as shown in figure 4.4-4. Consequently, this optimization case demonstrates the interdependence between I_{sb} and BV in this parameterization. Having measurement data for the Xyce-Dakota workflow to guide the optimization in the -6V to 0.6 V range may help optimization define independent I_{sb} and BV parameters in this dataset. Results of this optimization case are compared with the measurements in figure 5-3.

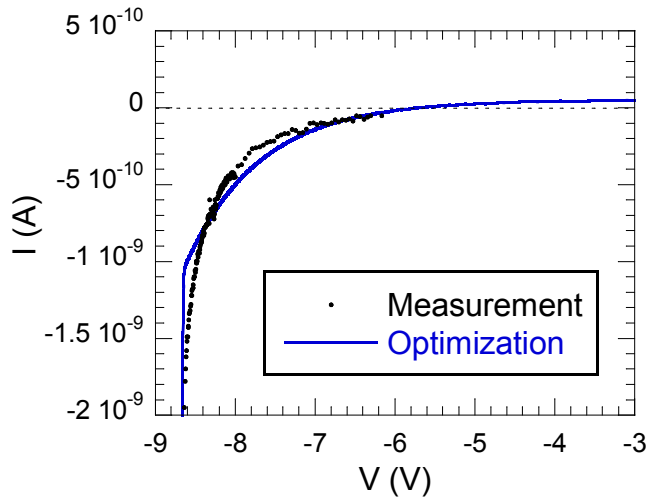
Generally, results suggest that a Xyce-Dakota workflow can optimize all 9 parameters if appropriately initialized and provide an excellent fit to the measured I-V curve, but connections to physical device behavior can easily be lost. Parameters found by Dakota-Xyce optimization are highly dependent on initial guesses, bounds, chosen objective functions and minimization criteria and are blind to physical phenomena that an electric circuit model may represent. Unique parameter sets are difficult to obtain, but dependences between parameters can be easily identified. In the case of this particular dataset, a best approach to obtain a good fit to the experimental data seemed to be to identify the initial parameters using the approach in section 4 for the applied circuit model shown in figure 2-1. Set I_{sb} to a low nominal fixed value, at least less than 1×10^{-14} , then optimize BV while holding all other parameters fixed.



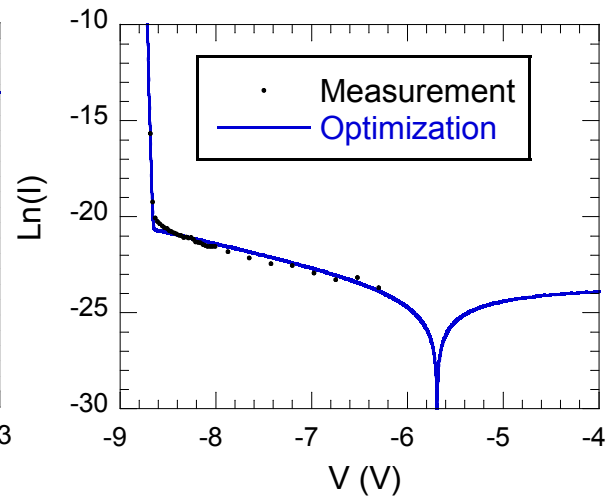
(a)



(b)



(c)



(d)

Figure 5-3: Optimized result compared with measured behavior using case II optimization approach, where several reverse parameters are optimized. Forward behavior on a (a) linear current vs. voltage plot and (b) $\ln(\text{current})$ vs. voltage plot. Reverse behavior on a (c) linear current vs. voltage plot and (d) $\ln(\text{current})$ vs. voltage plot.

Table V Results from optimizing selected reverse parameters				
Parameter	Initial Value	Optimized Value	Lower Bound	Upper Bound
#I _{sf}	4.422x10 ⁻¹⁶	4.422x10 ⁻¹⁶	-	-
#n _f	1.002	1.002	-	-
#R _f	1.683	1.683	-	-
I _{sb}	1 x10 ⁻¹⁵	5.17 x10 ⁻¹¹	1 x10 ⁻¹⁸	1 x10 ⁻¹⁰
#n _b	0.2081	0.2081	-	-
BV	8.654	8.64086	8.4	8.8
R _b	12.804	12.506	1	100
#I _{sl}	8.881 x10 ⁻¹⁴	8.881 x10 ⁻¹⁴	-	-
n _l	37.81	35.52	10	50

5. PIRT (PHENOMENA IDENTIFICATION AND RANKING TABLE)

The Phenomenon Identification and Ranking Table or PIRT is a process by which specific component phenomenon are first identified, and secondly evaluated to assess how well each phenomenon is represented in simulation software. The results are finally ranked on a scale of 1 to 3 in two categories, physical understanding and model capability. The simulation software in which “Model Capability” is measured is Xyce. However, this table should be used as a general driver for guidance in circuit simulation and parameter extraction for diode library creation. The PIRT highlights the current state of diode modeling. This table should also be continually updated according to advances in code development and parameter extraction.

Typically the importance of each physical phenomenon is quantified according to the stockpile driver for which the PIRT is being developed. Although developed for the Zener diode, the PIRT in this report is intended to retain connection to diodes in a general sense, as this report is for the parameter extraction and library development can be leveraged for diodes in general. The importance for the ability to model a particular phenomenon is purely specific to the application.

Physical phenomena present in diode operation include avalanche breakdown, Zener breakdown, high-voltage breakdown, forward/reverse recovery, carrier generation/recombination in the depletion region, high frequency characteristics, $1/f$ noise fluctuations, and temperature effects. The phenomenon present is dependent on how the diode is being operated. Three regions of diode operation include forward active, reverse leakage, and reverse breakdown. Some phenomenon (forward/reverse recovery) occur when the device operation is switched between different regions. Some phenomenon (breakdown) is unique to only one region of operation. Some phenomenon (high frequency) can occur within all regions of diode operation. Depending on the region of operation different phenomena will require different levels of accuracy. For example, if the device is a Zener diode and is primarily operated in the reverse breakdown region, the level of accuracy required for the reverse/ forward recovery phenomenon low. However, one would like a very high accuracy for the Zener breakdown. Experimental data has been compiled by Org 1356 on several diodes from multiple projects. This vast amount of experimental data and electrical characterization can be used to support phenomena identification, calibration, and code implementation.

Table VI Phenomena Identification and ranking table

Phenomenon	Importance	Physical understanding	Model capability	Comments
Avalanche breakdown	High	3	2	Complex physics represented by very limited set of parameters in a diode model
Zener breakdown	High	3	3	Not a lot of distinction between Zener, hv and avalanche breakdown in a compact model
High-voltage breakdown	High	3	3	Not relevant for Zener diode
Reverse recovery	Medium	3	3	Circuits that frequently oscillate between forward and reverse bias will be highly effected by recovery time
Forward recovery	Medium	3	3	Circuits that frequently oscillate between forward and reverse bias will be highly effected by recovery time
Carrier generation/recombination in depletion region	Medium	2	2	Ideal diode model assumes no carrier generation/recombination. Xyce parameter isr
Temperature effects	Medium	2	2	Temperature dependence of modeling parameters, as well as temperature compensating diodes
High frequency characteristics	Medium	2	2	Important for high speed applications. Rf characterization required for model inclusion
1/f noise fluctuations	Medium	2	2	Important for low noise applications. Noise characterization required for model inclusion

6. SUMMARY AND CONCLUSIONS

A scheme for parameter extraction of a Zener Diode to be adapted to the proposed approach of *Compact Model Development and Optimization Environment* (CoMoDOE) is presented in this report. A circuit model is defined and initial parameters are extracted from measured data to generate a simulation result of the electrical behavior of a real Zener diode. Once initial parameter extraction is complete, an optimization scheme is used to account for interdependencies between parameters and to improve the accuracy of the simulated behavior against the measured response. Optimization was developed and subsequently performed using a ‘Xyce-Dakota’ workflow, a new method for optimizing circuit models. Examining this scheme of initial parameterization followed by optimization of a electrical circuit model of real Zener diode behavior led to the following conclusions:

- Parameters between each branch (forward, reverse leakage and reverse block) in the circuit model are only loosely coupled. However, two parameters within the reverse breakdown branch of the circuit model are mutually dependent on one another, BV – the breakdown voltage and I_{sb} – the block diode leakage current. An identical fit to the real diode behavior can be achieved by fixing one of these parameters to a value then varying the other (section 4.3). This coupling separates the empirically determined values of the parameters from the physical behavior within a real Zener diode that these parameters are intended to represent.
- Blind optimization using a Xyce-Dakota workflow can provide an excellent fit to the measured data. however the derived parameters can be *non-physical* and even ‘*non-sensical*,’ *i.e.*, no longer attached to the physics of operation of the device for which they are derived. The strong coupling between the block diode parameters, the very weak coupling between the parameters from the different model circuit branches contribute to this issue.
- Accurately fitting data representing a real Zener diode I-V response across 10 or more orders of magnitude is a challenge for any optimization routine.
- The results from this study strongly suggest a ‘data driven strategy to optimization’. Individual measurements will likely need to be handled, or at least inspected separately. Constraints on the optimization process will have to be applied and wisely chosen to achieve consistent physically-based parameters from a circuit model representing real device behavior.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. Keiter, E.R., Aadithya, K.V., Mei, T., Russo, T.V. Schiek, R.L., Sholander, P.E., Thornquist, H.K. and Verley, J.C. *Xyce Parallel Electronic Simulator Reference Guide, Version 6.6*. SAND2016-1175, Sandia National Laboratories, Albuquerque, NM.
2. Adams, B.M., Ebeida, M.S., Eldred, G.G., Jakeman, J.D., Maupin, K.A., Monschke, J.A., Swiler, L.P., Stephens, J.A., Vigil, D.M., Wildey, T.M., Bohnhoff, W.J., Dalbey, K.R., Eddy, J.P., Frye, J.R., Hooper, R.W., Hu, K.T., Hough, P.D. Khalil, M., Ridgway, J. *Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis, Version 6.6 User's Manual*. SAND2014-4633, Sandia National Laboratories. Albuquerque, NM, July 2014.
3. "<https://www.onsemi.com/pub/Collateral/MMSZ5221BT1-D.PDF>."
4. Deveney, M. 1992. "A Temperature Dependent Spice Macro-Model for Zener and Avalanche Diodes." *Proceedings of the 34th Midwest Symposium on Circuits and Systems, Vols. 1 and 2*. I.E.E.E. 592-596.
5. Laha, A.K. and Smart, D.W. 1981. "A Zener Diode Model with Application to SPICE2." *IEEE Journal of Solid-State Circuits* SC-16 (1): 21-22.
6. Massobrio, G. and Antognetti, P. 1993. *Semiconductor Device Modeling with SPICE, 2nd. Ed.* New York: McGraw-Hill.
7. Keiter, E., Swiler, L. Russo, T. and Wilcox, I. *Sensitivity Analysis in Xyce*. SAND2016-9437, Sandia National Laboratories, Albuquerque, NM Sept. 2016.
8. *B1505A Power Device Analyzer / Curve Tracer Users Manual*, Keysight Technologies <http://www.keysight.com>
9. Moll, J.L. and Ebers, J.J., "Large-Signal Behavior of Junction Transistors", *Proceedings of the IRE*, vol 42, no. 12, pp. 1761-1772, 1954.
10. <http://www.wolfram.com/>.

9. APPENDIX

A.1 Xyce Netlist used in Optimization

```
* Zener Model for Comodoe

VZ 1 0 DC
XZ 1 0 ZenerModel

.SENS param =
+ XZ:VB:DCV0,
+ XZ:RB:R,
+ DBLOCK:is,
+ DBLOCK:n,
+ DLEAK:is,
+ DLEAK:n
+ objfunc={ln(abs(I(VZ)))}
.PRINT SENS FORMAT=noindex V(1)

.DC VZ -10.0 0.0 0.01
.print dc format=noindex file=zenerDiode.rev.out
+ V(1)
+ {ln(abs(I(VZ)))}

.SUBCKT ZenerModel 1 2
D1 1 2 DFWD
D2 2 1 DLEAK
D3 4 3 DBLOCK
VB 3 1 V_break
RB 4 2 R_break
.ENDS ZenerModel

* Models
.MODEL DFWD D
+ IS = 1.26528023112e-14 N = 1.11980416249 RS = 0.977844777311
+ BV = 1000 IBV = 0.001 EG = 1.11
.MODEL DLEAK D
+ IS = IS_leak N = N_leak
.MODEL DBLOCK D
+ IS = IS_block N = N_block

.END
```

Highlighted text are placeholders for Dakota replacements of electrical parameters

Dakota Input Deck

```
responses
  calibration_terms = 1
  scalar_calibration_terms = 0
  field_calibration_terms = 1
  num_coordinates_per_field = 1
  read_field_coordinates
  # Lengths would be dependent on the number of entries in the data set
  lengths= 1001
  num_experiments = 1
  calibration_data
  interpolate
  response_descriptors = 'ZR'
  analytic_gradients
  no_hessians

variables
  continuous_design = 6
  initial_point 8.715, 15.3012092378, 5.60943002922e-11, 871.467287118, 1e-20, 0.0544644342707
  lower_bounds 7.92272727273, 1.53012092378, 5.60943002922e-17, 8.71467287118, 1e-22, 0.000544644342707
  upper_bounds 9.5865, 153.012092378, 5.60943002922e-05, 87146.7287118, 1e-14, 5.44644342707
  descriptors 'V_break', 'R_break', 'IS_leak', 'N_leak', 'IS_block', 'N_block'

environment
  tabular_data
  tabular_data_file 'dakota_tabular.out'
  output_file 'dakota.out'
  error_file 'dakota.err'
  write_restart 'dakota.rst'

interface
  id_interface = 'ZI'
  fork
  asynchronous
  evaluation_concurrency 8
  analysis_driver = 'analysis_driver_rev'
  parameters_file = 'params.in'
  results_file = 'results.out'
  aprepro
  file_save
  work_directory
    named 'workdir'
    directory_tag
    directory_save
    copy_files '*.template*'

model
  single

method
  nl2sol
  convergence_tolerance = 1.0e-6
```

Highlighted regions indicates what the python script initializes values in Dakota script.

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